NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 3428

GROUND-SIMULATOR STUDY OF THE EFFECTS OF STICK FORCE AND DISPLACEMENT ON TRACKING PERFORMANCE

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SUMMARY

An investigation has been made to obtain an indication as to the desired magnitudes of the pilot's stick forces and stick displacements in relation to the tracking performance. The tests have been performed on a ground simulator with one degree of freedom, pitch. The stick force and stick displacement per unit response were variable, and the period and damping characteristics could be adjusted to cover the ranges existing for most airplane types. For this investigation the period and damping of the ground simulator were typical of those of current fighters operating at low altitudes and at subsonic speeds.

The results of the tests for a well-damped airplane show that, as the required stick displacements were reduced, the accuracy of the subjects in performing the tracking task improved. The tests also showed that, as the force required was reduced, the accuracy improved.

The control technique used by the subjects in this investigation may be somewhat different from that used in actual flight. In these tests, the subjects utilized a procedure to improve the response of the airplane wherein much more force and displacement were applied than were required to give steady-state response. In actual tracking flight, the control procedure may be conditioned by other factors, and control applications may be somewhat slower and more deliberate.

INTRODUCTION

The design of the pilot's primary control, that is, the amount of displacement of the control stick required to deflect the control surface, usually has been based on the desire for the highest possible mechanical advantage compatible with both the cockpit size and the reach of the pilot. Investigations of the effects of control-stick displacement and related force characteristics on the pilot's abilities in performing a specific task have not generally been made. With the higher speeds and the more exacting requirements of today's flying, a more precise determination of control displacement and force characteristics is needed. In addition, the use of power-actuated controls and mechanical-feel systems in which the stick is not directly connected to the control surface gives the designer greater flexibility in the selection of the amount of stick displacement and stick force required to produce a given airplane response. The research program covered in this report was undertaken to provide an indication as to the desired magnitudes of the stick displacements and of the stick forces in relation to the performance of a tracking task.

The tests were performed on a ground simulator with one degree of freedom, pitch. The stick force and stick displacement per unit response were varied, and the period and damping characteristics were adjusted to simulate those of typical present-day fighter airplanes operating at low altitudes and subsonic speeds. Using the simulator, a group of subjects attempted to track a randomly moving target. Various combinations of stick force and stick displacement per unit response were investigated and were evaluated on the basis of the average tracking error of each subject.

This report contains the test results for a range of stick-displacement gearing at two different values of stick force per unit response. For these tests the simulated airplane had an undamped natural frequency of 1/2 cycle per second and a damping ratio of approximately 0.8.

SYMBOLS

a_n	normal acceleration, g units
$\bar{c}$	mean aerodynamic chord, ft
D	operator, $\frac{\bar{c}}{V}\frac{d}{dt}$
$\frac{dF_s}{d\alpha}$	static force gradient, lb/deg
$\frac{dX_s}{d\alpha}$	static stick gearing, in./deg

F_s	stick force, lb
g	acceleration due to gravity, ft/sec^2
t	time, sec
V	velocity, ft/sec
X_s	stick displacement, in.
α	angle of attack, deg
δ_s	stick deflection, deg
θ	pitch angle, deg
ψ	simulator deflection, deg
A, B, C, E, F, G, J, K, P, Q	constant coefficients

Subscripts:

A	airplane
S	simulator

DESIGN CONSIDERATIONS

A simple mechanical system that was capable of reproducing the longitudinal characteristics of an airplane was desired. The second-order system consisting of a mass, a spring, and a dashpot, which was selected, would satisfactorily reproduce the period and damping of the short-period oscillation of the airplane but would have a response to control applications differing from that of conventional airplanes to the extent discussed in the following paragraphs. In brief, the differences are that, on the simulator, a given control application would produce a given steady-state displacement or, in effect, a given pitch angle. On most airplanes, for low-frequency stick inputs, a given control application would produce (if the very-long-period phugoid mode is neglected) a given steady-state normal acceleration which shows up visually to the pilot as a continually increasing pitch angle, the rate being proportional to the normal acceleration. At higher stick-input frequencies on the order of or greater than one-half the frequency of the short-period oscillation, the airplane pitch response and that of the simulator become alike.

The following transfer functions of the simulator response and of the airplane response for two degrees of freedom (determined from ref. 1) show the exact extent of simulation:

$$\left(\frac{\psi}{\delta_s}\right)_S = \frac{J}{ED^2 + FD + G}$$

$$\left(\frac{\theta}{\delta_s}\right)_A = \frac{K + \frac{C}{D}}{ED^2 + FD + G}$$

$$\left(\frac{a_n}{\delta_s}\right)_A = \frac{V}{g}\,\frac{AD^2 + BD + C}{ED^2 + FD + G}$$

$$\left(\frac{\alpha}{\delta_s}\right)_A = \frac{PD + Q}{ED^2 + FD + G}$$

In these equations the denominator represents the characteristic equation of the system which determines the period and damping. In the airplane pitch transfer function $(\theta/\delta_s)_A$, the coefficient K for current airplanes roughly varies from 3 to 15 times greater than the coefficient C. Thus, for moderate to high frequencies the response of the simulator is seen to be of similar form to the pitch response of the airplane. It can be demonstrated that for most airplanes this similarity exists for frequencies greater than one-half the natural frequency. (For example, see fig. 19 of ref. 1.)

In the airplane normal-acceleration transfer function $(a_n/\delta_s)_A$, the coefficient B is negligible for most airplanes. At low frequencies the value of the transfer function would be dominated by the term C/G and at high frequencies by the term A/E (tail lift contribution). For most airplanes the term A/E would be small compared with the term C/G. Thus, the simulator response is seen to be similar to the airplane normal-acceleration response, the similarity being exact at low frequencies.

In the angle-of-attack transfer function $(\alpha/\delta_s)_A$, the coefficient P is small compared with the coefficient Q. The simulator is thus seen to approximate closely the angle-of-attack response of the airplane throughout the frequency range. However, angle of attack is not readily sensed by the pilots and therefore it is not felt that the simulator could be assumed to represent control of this variable. On the other hand, the static relationship between stick displacement and simulator angular response can be compared directly with the corresponding airplane static-stability parameters $\frac{dX_s}{d\alpha}$ and $\frac{dF_s}{d\alpha}$. Since these parameters can be determined for any airplane, the simulator static response characteristics are quoted in terms of these airplane parameters.

APPARATUS

A photograph and a diagrammatic sketch of the ground simulator used in the investigation are shown in figures 1 and 2, respectively.

The heart of the simulator was the mass-spring-dashpot system previously discussed which reproduced the period and damping characteristics of the airplane. The complete simulator included a control stick connected with adjustable gearing to an "elevator" T-bar. The T-bar was connected to the simulation system by springs, and deflection of the T-bar introduced moments into the system. The natural frequency could be varied by proper positioning of the mass and the springs, and the damping ratio could be varied by proper selection of the damping fluid.

The moment of inertia of the airplane system was kept very low; therefore, for a wide range of gearing between the T-bar and the stick (even approaching zero stick movement), there could be no perceptible force feedback to the stick from this source. All stick forces felt by the subject were produced by cantilever springs fastened to the frame of the simulator and attached to the control stick by means of a push-pull rod. All push-pull rods in the simulator were preloaded by springs so as to keep backlash to a minimum.

A wheel type of control stick was used, but the subject was allowed to hold the control as he pleased, with one hand or two, with finger tips or full grip. He was also allowed to support his hands and arms in any manner he wished. The moment of inertia of the stick was 2 slug-feet^2, and the friction in the pivots was negligible compared with the stick force gradient.

The recording system used was a mechanical-optical type and recorded as a continuous trace on photographic film. Basically, the system consisted of a pair of mirrors, one mirror (recording mirror A) attached to the airplane simulator and the other (recording mirror C) to the cam follower (see fig. 3). The two mirrors had a common axis of rotation and were mounted so as to be at 90° to each other whenever there was zero tracking error. Light from a point source was reflected from mirror A to mirror C and then to the moving film. Similarly, light was reflected from recording mirror C to recording mirror A and then to the film. This setup gave two light paths which produced two traces on the film. These two traces intersected whenever the angle of the mirrors was exactly 90° (zero tracking error). A change in angle of the mirrors from 90° deflected the traces in opposite directions by an equal amount, an amount directly proportional to the tracking error. Inasmuch as the two traces were the inverse of each other and to make the best use of the film, the intersection line was set near the bottom of the film and, in effect, only the absolute value of the error was recorded. Film records of approximately 1-minute duration were taken, and these records were integrated by using a mechanical integrator to determine the average error and also the root-mean-square error (standard deviation). Figure 4(a) shows a sample record, and figure 4(b) shows a record of the error when the airplane was maintained at zero pitch angle (no tracking effort by the subject). For clarity in presentation, the traces below the zero line have been omitted. With the airplane held at zero pitch angle, the average tracking error was 19 mils and the root-mean-square tracking error was 23.4 mils.

TESTS AND PROCEDURE

The subject, sitting in a pilot's seat, saw two horizontal bars of light projected on a blackened wall in front of him. One of the light bars moved in response to stick deflections and, as such, represented the simulated-airplane motions. The other light bar had a random motion and represented the target motions. In operation, the subject attempted to keep the two bars of light together.

The motions of the target light were produced by a cam (see fig. 2(a)) driven at 1 revolution per minute. The cam was designed to provide a target motion equal to the summation of the first 24 harmonics of a sine curve. The harmonics were all of equal amplitude but had random phase relationships. The target motion was adjusted to have a maximum amplitude of ±60 mils and the highest input frequency was 0.43 cycle per second. A time history of the target motion is shown in figure 5.

Another piloting task that was investigated involved having the subject attempt to regulate random pitching moments (similar in nature to gusty air). In these tests the cam acted on one of the simulator springs to produce a disturbing moment on the airplane (see fig. 2(b)). The subject tried to counteract this moment so as to keep the airplane at zero pitch angle. The same cam was used and, for the airplane tested, the response was adjusted to produce a maximum disturbance of ±35 mils. The cam was driven four times as fast as it was in the tracking tests to produce a frequency content that varied from 1.6 to 0.25 cycles per second.

Nine subjects were used in the investigation. These included four professional test pilots, two pilots who flew regularly with the U. S. Naval Reserve, and three nonpilots. At the beginning of the tests sufficient time was given to each of the subjects so that he could become completely familiar with the operation of the simulator and could stabilize his tracking performance. Some of the subjects required as much as 60 minutes to complete this learning phase. After completion of this learning period, there was no consistent variation of performance level with the flight experience of the subject.

For each test condition, the standard procedure was to have the subject make a test run consisting of 4 minutes of practice followed by a 1-minute record. During a period of 2 or 3 days three such test runs were made by each subject and a single value of tracking error was determined for the three records by an averaging procedure. Records which were obviously not representative of consistent tracking (repeatability within 1/2 mil) and records taken during the learning phases were not used. The single value thus obtained was considered to be the lowest that could be consistently repeated by the subject with the particular condition under test. Although the cam required 1 minute to recycle and was operated both forward and backward, it was discovered early in the tests that the subjects could remember certain pertinent features of the target motion. To eliminate this learning, a second cam (based on the cosine summation of the harmonics used for the original cam) was made and used for practicing, the first cam being used for recording.

For these tests the simulated airplane had an undamped natural frequency of 1/2 cycle per second and a damping ratio of approximately 0.8. For the tracking investigation, tests were made at a force gradient $\frac{dF_s}{d\alpha}$ of 6 pounds per degree with stick gearings $\frac{dX_s}{d\alpha}$ of 0.015, 0.3, 0.6, 1.2, and 1.8 inches per degree. These values correspond to a force of 20 pounds and displacements of 0.05, 1, 2, 4, and 6 inches required for full deflection of the airplane light bar. Another force condition tested had a gradient of 0.45 pound per degree with gearings of 0.015, 0.3, and 1.2 inches per degree. These values correspond to a force of $1\frac{1}{2}$ pounds and displacements of 0.05, 1, and 4 inches required for full deflection of the light bar. Points were also obtained for the condition of a stick force gradient of 3 pounds per degree and a stick-displacement gearing of 1.2 inches per degree and for the condition of a stick force gradient of 1.5 pounds per degree and a stick-displacement gearing of 0.015 inch per degree.

Tests of the gust type of input were made only at the conditions of a stick force gradient of 6 pounds per degree and stick-displacement gearings of 0.015, 1.2, and 1.8 inches per degree.

RESULTS AND DISCUSSION

The response of the simulator to a stick displacement was not exactly the same as that of airplanes, as previously discussed. However, the human readily adapts himself to various types of responses, and it is felt that the results obtained on the simulator would be an indication of the trends to be found in the control of airplanes. This assumption would, of course, require proof by similar tests performed in flight. Equipment similar to the simulator of this investigation has been successfully used in ground tests of several airplane control systems.

The results of the tests are presented in figures 6 to 10 in terms of both the average tracking error and the root-mean-square tracking error. These figures give the individual subject's score at each condition and also show a series of trend lines. These trend lines were obtained by averaging, at two adjacent test conditions, the results for all those subjects who had test points for both conditions. The number of subjects used in obtaining the trend lines varied from 8 to 3.

Figure 6 shows the effects of varying the stick gearing for a stick force gradient of 6 pounds per degree. Figure 7 shows the effects of varying the stick gearing for a stick force gradient of 0.45 pound per degree. Figure 8, a cross plot of figures 6 and 7, shows the effects of varying the force gradient for several stick gearings. Figure 9 presents results summarized from figures 6, 7, and 8 and shows what might be considered the performance of the average subject. Figure 10 presents results obtained from the gust type of inputs.

The tracking task presented to the subject contained a very large proportion of high-amplitude—high-frequency target motion. In air-to-air tracking, high-frequency target motions are limited to very small amplitudes. Inasmuch as the ability to track these high-frequency motions was limited by the response of the airplane-subject combination, the general level of the tracking error in these tests was greater than that expected for visual tracking in flight. The trends as obtained from this investigation are expected to apply to flight conditions, but in view of the differences in target motion, the magnitudes of the effects of the variables studied may be different.

Figures 6 and 7 show that reducing the required displacements of the stick increased the tracking accuracy. For the 6-pound-per-degree case (fig. 6), this increase in tracking accuracy amounted to roughly 25 percent between the extreme gearings of 1.8 and 0.015 inches per degree. Some of this improvement was thought to be due to the reduced influence of the inertia of the subject himself, caused by the reduced arm and body motions required. In the extreme case of the rigid stick, an application of force would instantaneously produce the associated moment on the airplane. Also, for the cases where small stick motions were required, it was possible for the subject to utilize successfully a control procedure to improve the response of the airplane wherein more force and displacement were applied than were required to hold the steady-state response. It was observed in the tests that two or three times the forces required for maximum (60-mil) steady-state airplane-light-bar deflection were used to accelerate or to check the airplane motions. In actual flight when tracking a target, the pilot's control procedure may bé conditioned by other factors such as the loads being applied to the airplane; therefore, his control technique may be somewhat different from that adopted by the subjects for these tests. In actual tracking, the pilot may use somewhat slower, more deliberate control applications which might cause the quality of the tracking to deteriorate.

Figure 8 shows generally that reducing the force gradient also increased the tracking accuracy. Between the extreme cases of 6 pounds per degree and 0.45 pound per degree, the increase in tracking accuracy amounted to roughly 20 percent. For the low but perceptible stick forces the subject was not required to use any arm or back muscles but could and did displace the stick by using only wrist and finger motions. In fact, the subjects, with one exception, supported their arms on their legs for the low-force tests. The use of only wrist and finger motions allowed more rapid applications and reversals of stick force. The improvements in tracking performance with reduction in force gradients were not without deterrents. These deterrents are evidenced by the increased scatter of the test points and also, for the case of a rigid stick and low force, by the relatively small number of subjects presented. The small number of subjects for which data are presented is due to a lack of satisfactory consistency for any of the other subjects. This result indicates that with light forces and small displacements the airplane response is more subject to inadvertences due to momentary control lapses. Inasmuch as this type of control is not very familiar, perhaps substantial learning periods would be required before consistent results could be expected. Additional tests were made with no force spring attached to the stick, and these tests showed no further reductions in tracking error but, in fact, showed increased errors. There were, however, definite indications that with more practice and a more relaxed attitude the results of the no-force cases would be in line with the results of the 0.45-pound-per-degree condition.

The summary plot of figure 9 for the average subject shows that for force gradients of 6 and 0.45 pounds per degree the reduction in tracking error is about the same, approximately 2-mil average error between the extreme conditions plotted. The plot also shows the increase in tracking accuracy that results from decreasing the force gradient to the low value of 0.45 pound per degree. The points for 1.5 and 3 pounds per degree indicate that most of this improvement in tracking accuracy was due to the presence of very low control forces which enabled the subject to control by using only wrist and finger motions.

The results of the gust type of inputs, shown in figure 10, indicate the same trends for the 6-pound-per-degree gradient that are indicated by the tracking type of input (fig. 6). Therefore this type of testing was discontinued in the interest of expediency.

Stick force gradients as low as 0.45 pound per degree, even though superior for tracking-performance accuracy, may be relatively worthless for airplane installation because the effects of airplane acceleration on the pilot's hands and arms could produce forces on the stick. Also, if the stick were equipped with the usual switches and buttons, operation of these might produce airplane motion. It appears, therefore, that some moderate force level, with perhaps the currently acceptable minimum of 3 pounds per g, would be the minimum usable force gradient. This value, of course, applies to a floor-mounted stick. If an armrest-mounted controller were used, the minimum force gradient could possibly be less.

A general note about these tests is that the tracking performance of the pilot-airplane combination is dominated by the airplane dynamic response and is much less influenced by the force and displacement characteristics of the control stick. It appears therefore that an airplane that is correspondingly well damped and has a shorter period would show smaller tracking errors than the airplane simulated in this investigation.

CONCLUDING REMARKS

An investigation has been made on a single-degree-of-freedom (pitch) simulator on which the stick force, the stick motion, and the natural-frequency and damping characteristics of the simulated airplane could be varied to obtain an indication as to the desired magnitudes of the control-stick gearing and the force gradient in relation to the performance of a tracking task.

The results of tests for a well-damped fighter-type airplane show that, as the stick displacement required was reduced to almost zero, the tracking accuracy of the subjects improved. The tests also showed that as the force required was reduced the tracking accuracy improved.

The control technique used by the subjects in this investigation may be somewhat different from that used in actual flight. In these tests, the subjects utilized a procedure to improve the response of the airplane wherein much more force and displacement were applied than were required to give steady-state response. In tracking flight, the control procedure may be conditioned by other factors, and control applications may be somewhat slower and more deliberate.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., January 11, 1955.

REFERENCE

1. Stokes, Fred H., and Mathews, Charles W.: Theoretical Investigation of Longitudinal Response Characteristics of a Swept-Wing Fighter Airplane Having a Normal-Acceleration Control System and a Comparison With Other Types of Systems. NACA TN 3191, 1954.

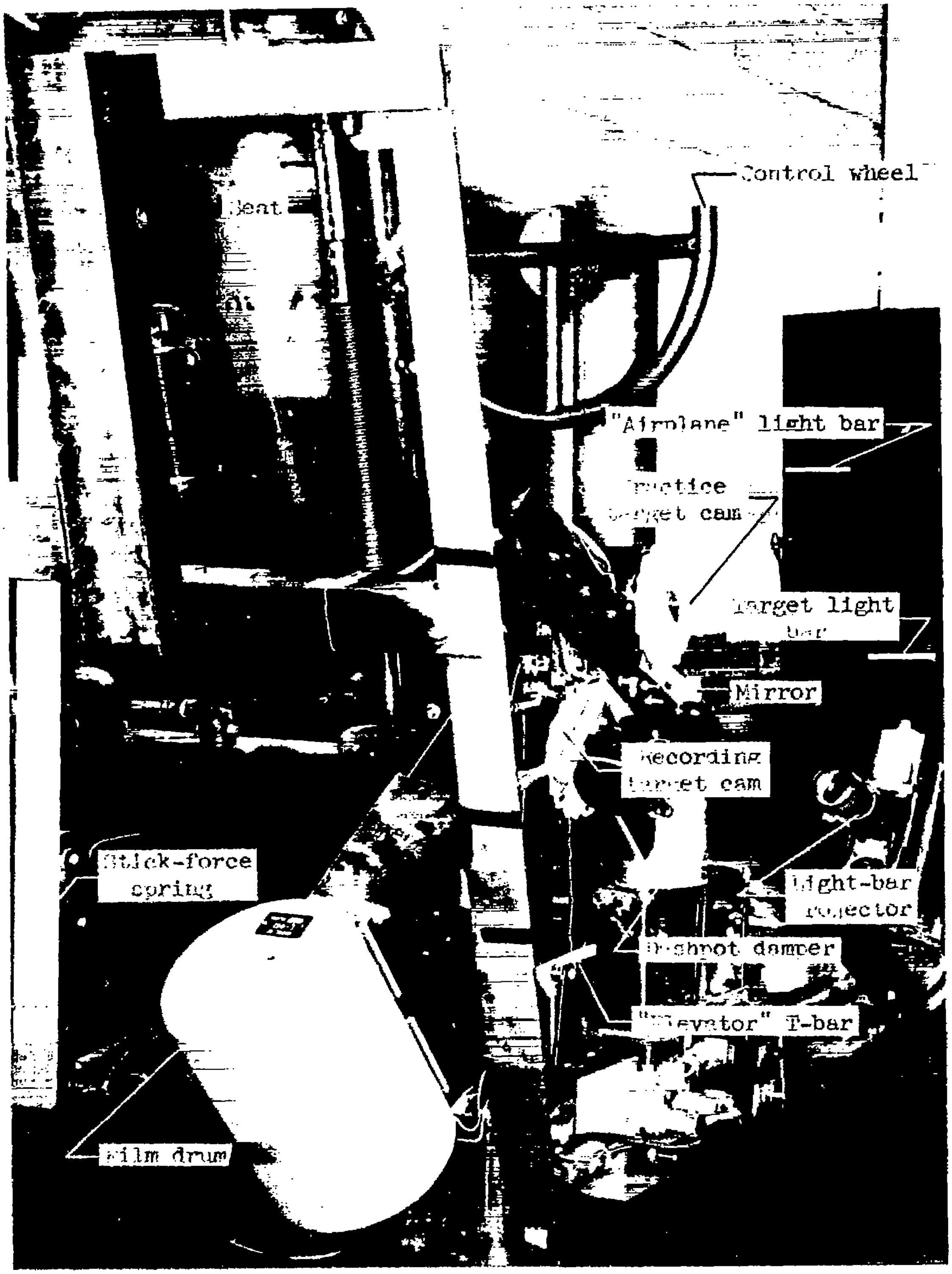


Figure 1.- Ground simulator used in investigation. L-85335.1

(a) Command tracking arrangement.

(b) Gust-type input arrangement.

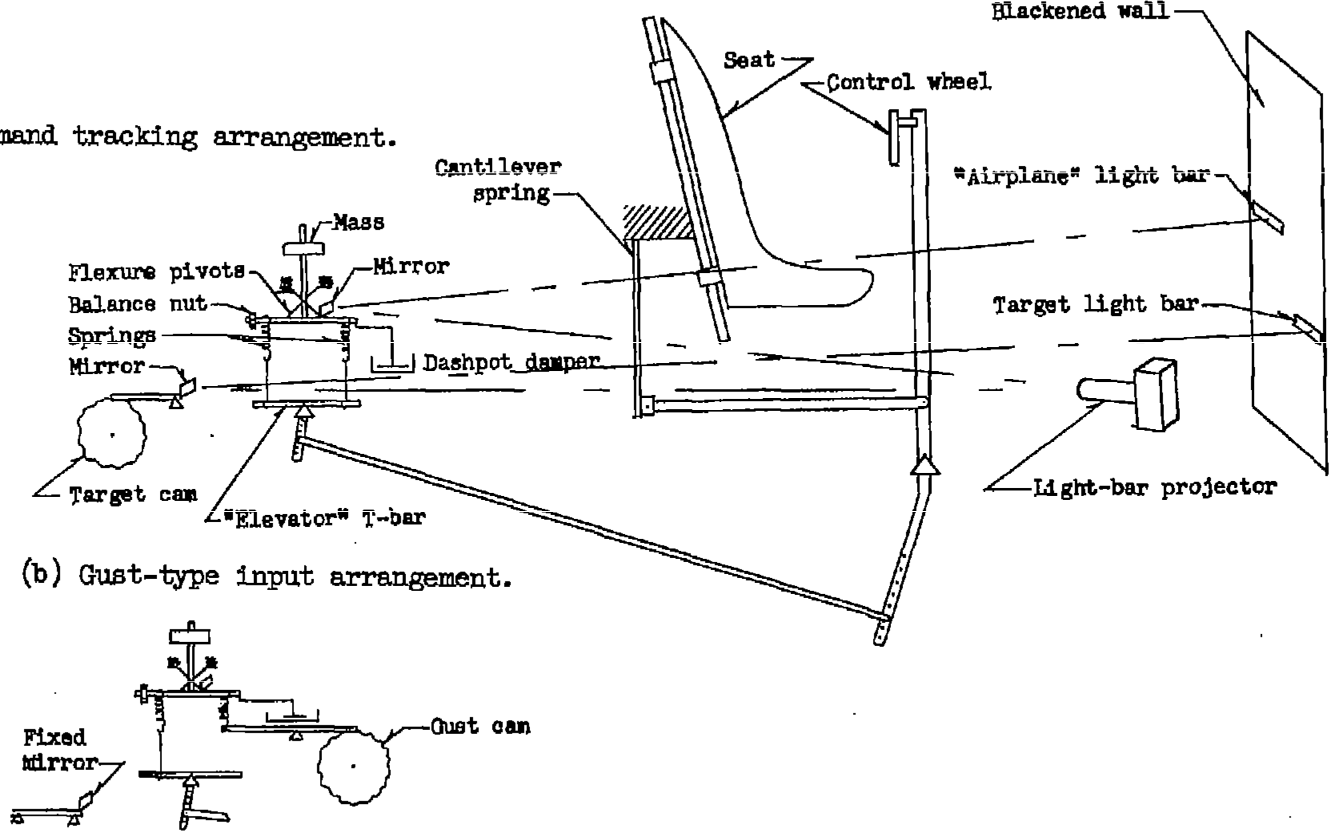


Figure 2.- Diagrammatic representation of simulator.

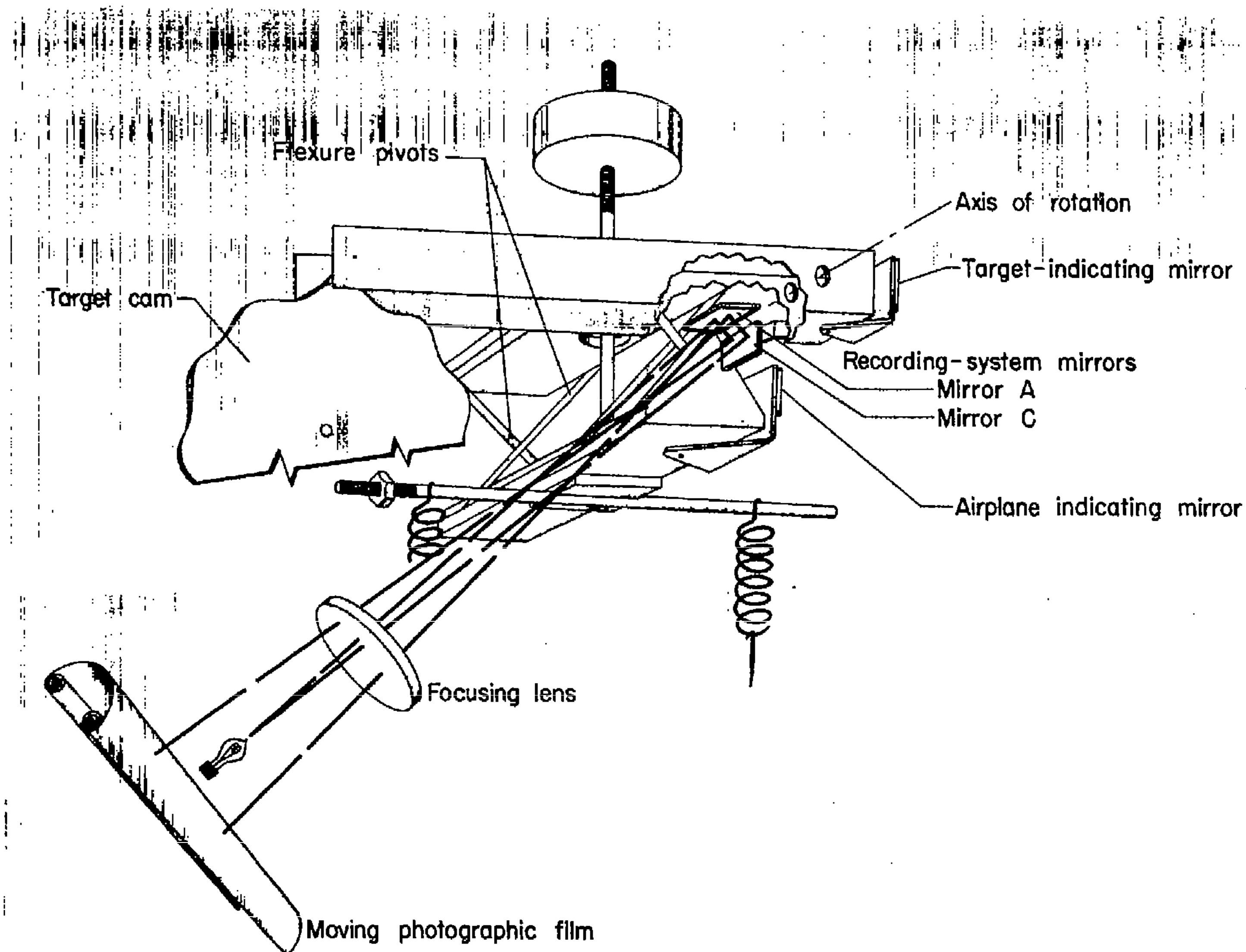
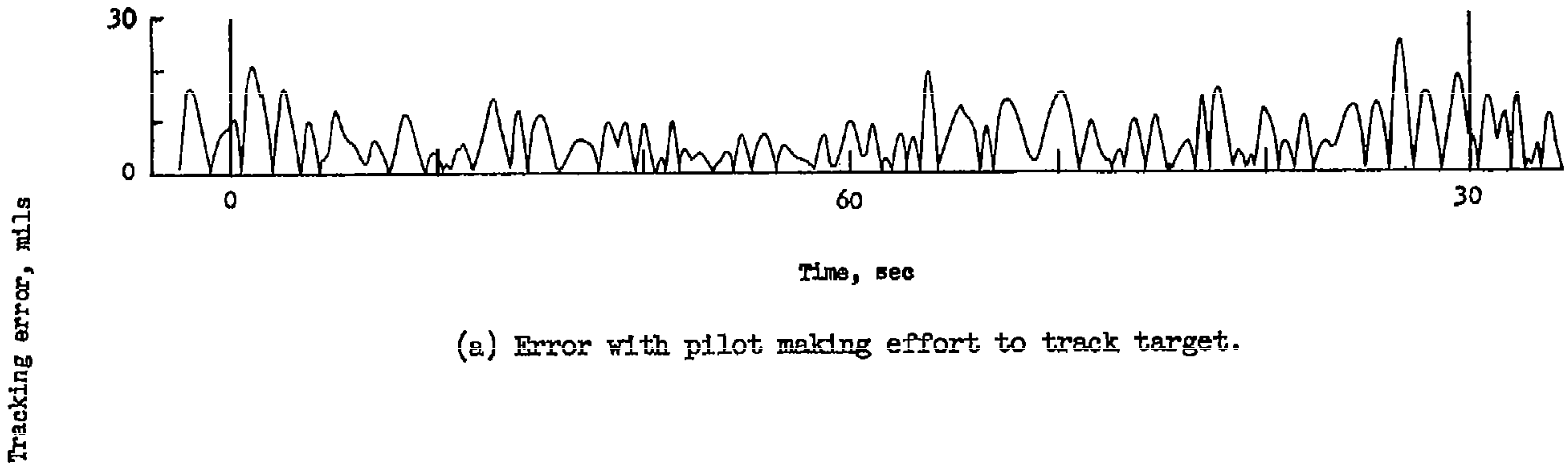
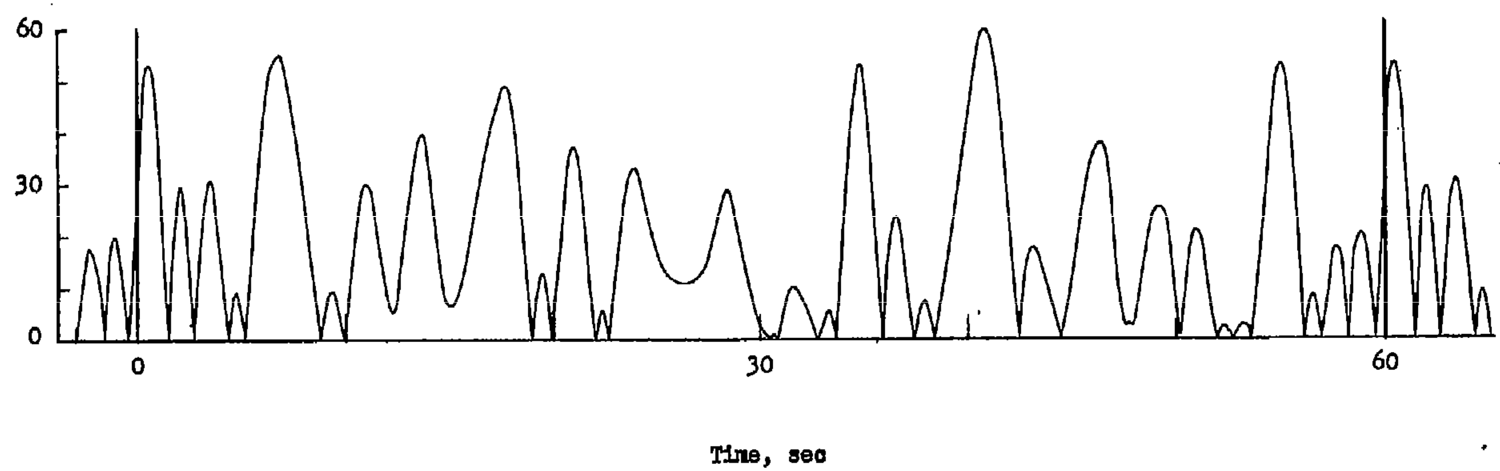


Figure 3.- Diagram of mechanical-optical recording system. L-87571



(a) Error with pilot making effort to track target.



(b) Error with airplane held at zero deflection.

Figure 4.- Sample records of tracking error for 1 cycle.

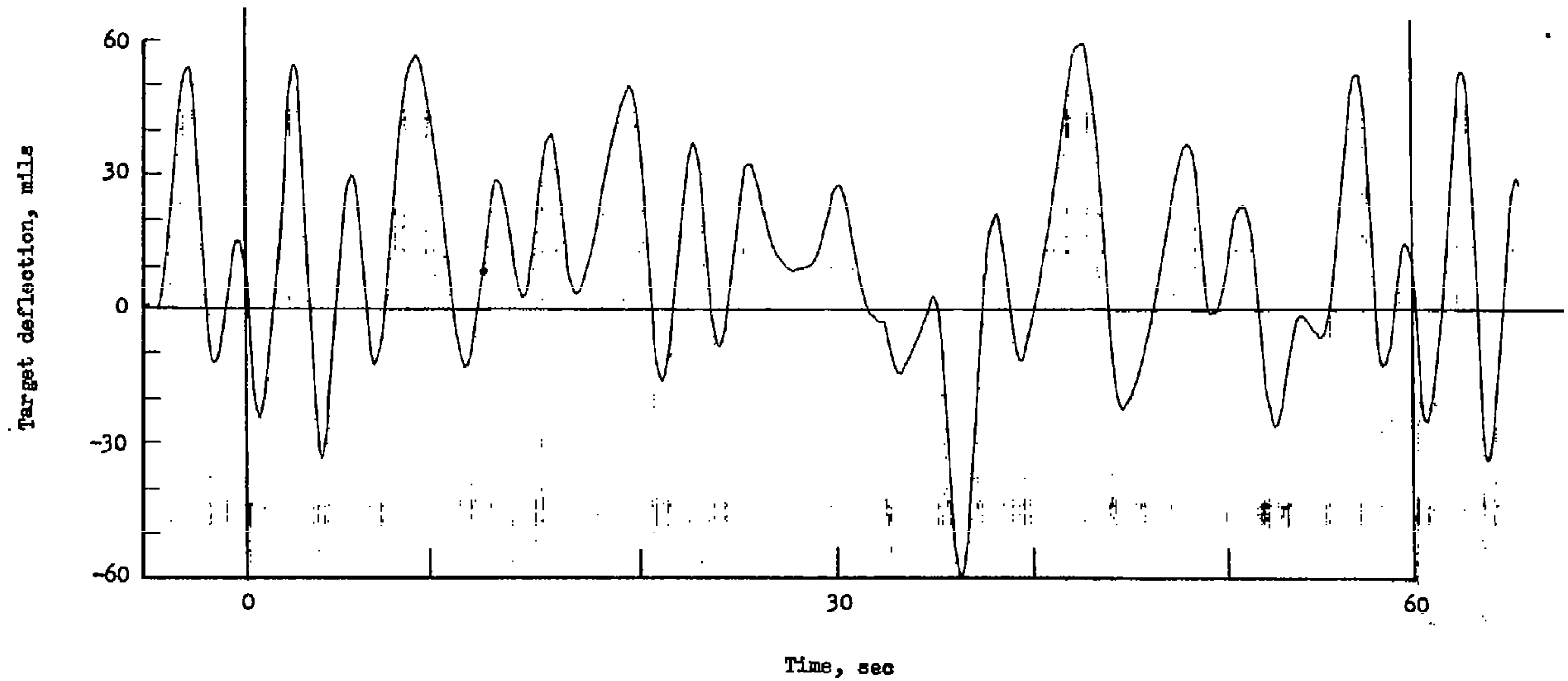


Figure 5.- Time history of target motion for 1 cycle.

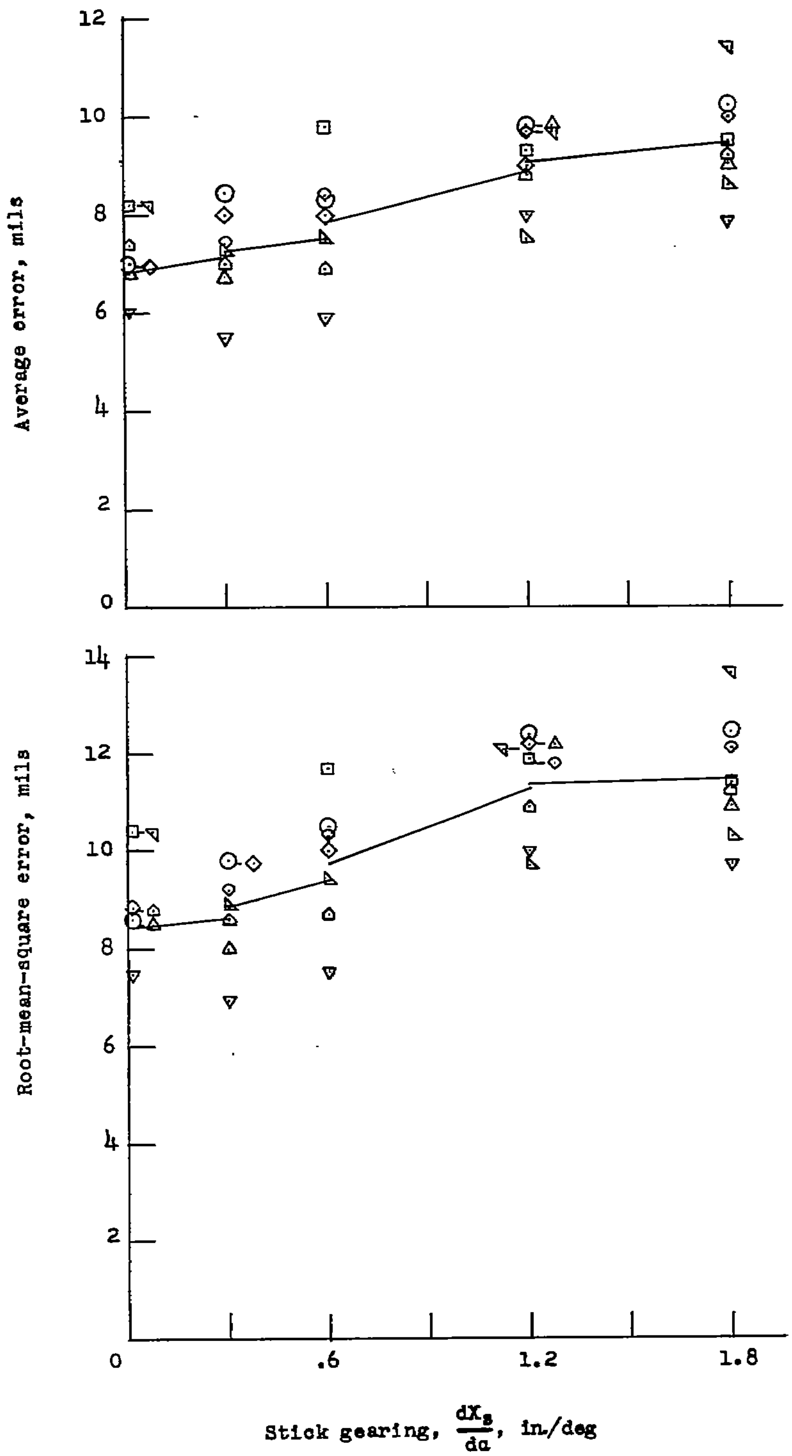


Figure 6.- Variation of representative tracking error with stick gearing for force gradient of 6 pounds per degree. Test-point symbols indicate different subjects.

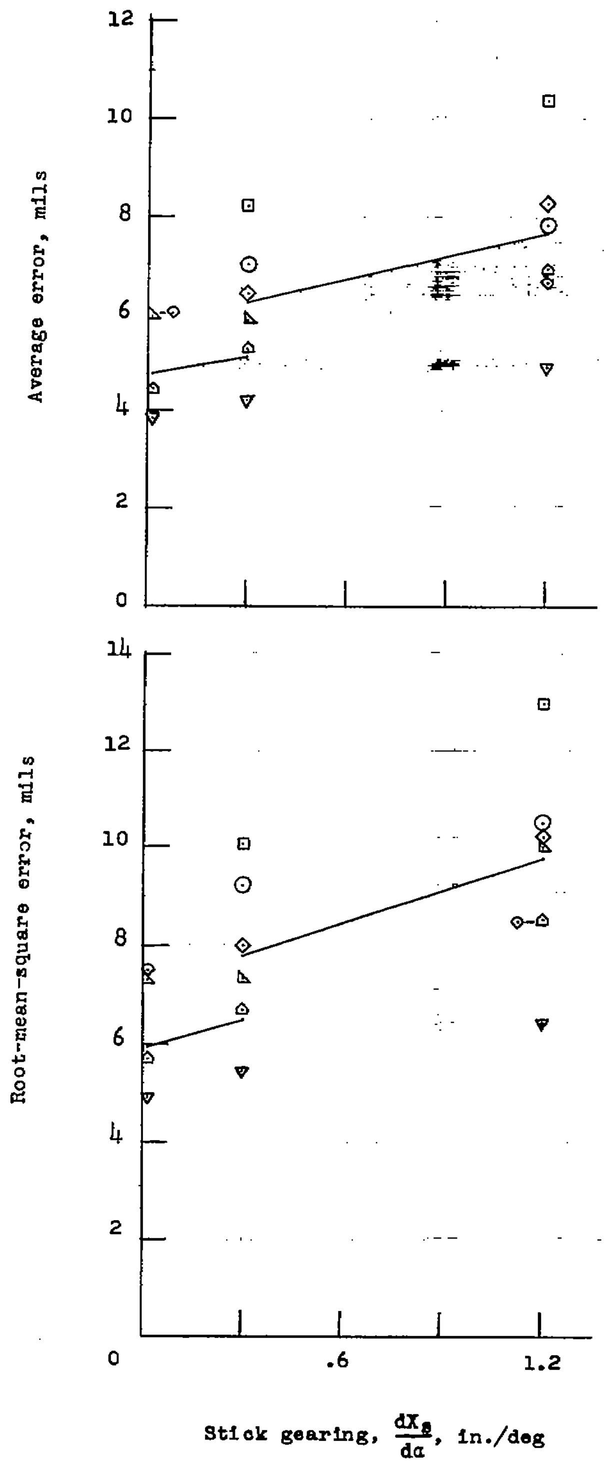


Figure 7.- Variation of representative tracking error with stick gearing for force gradient of 0.45 pound per degree. Test-point symbols indicate different subjects.

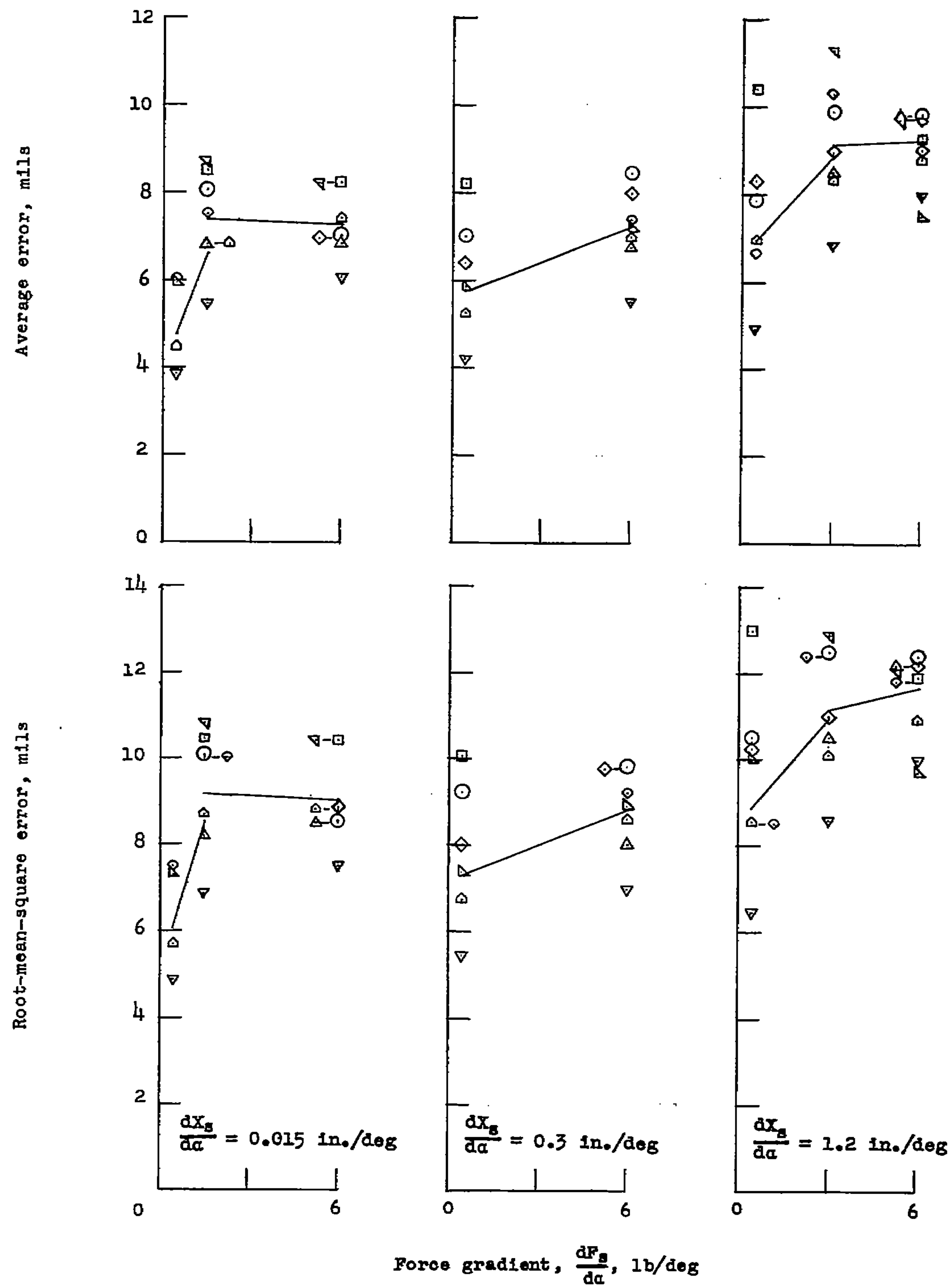


Figure 8.- Variation of representative tracking error with force gradient for several stick gearings. Test-point symbols indicate different subjects.

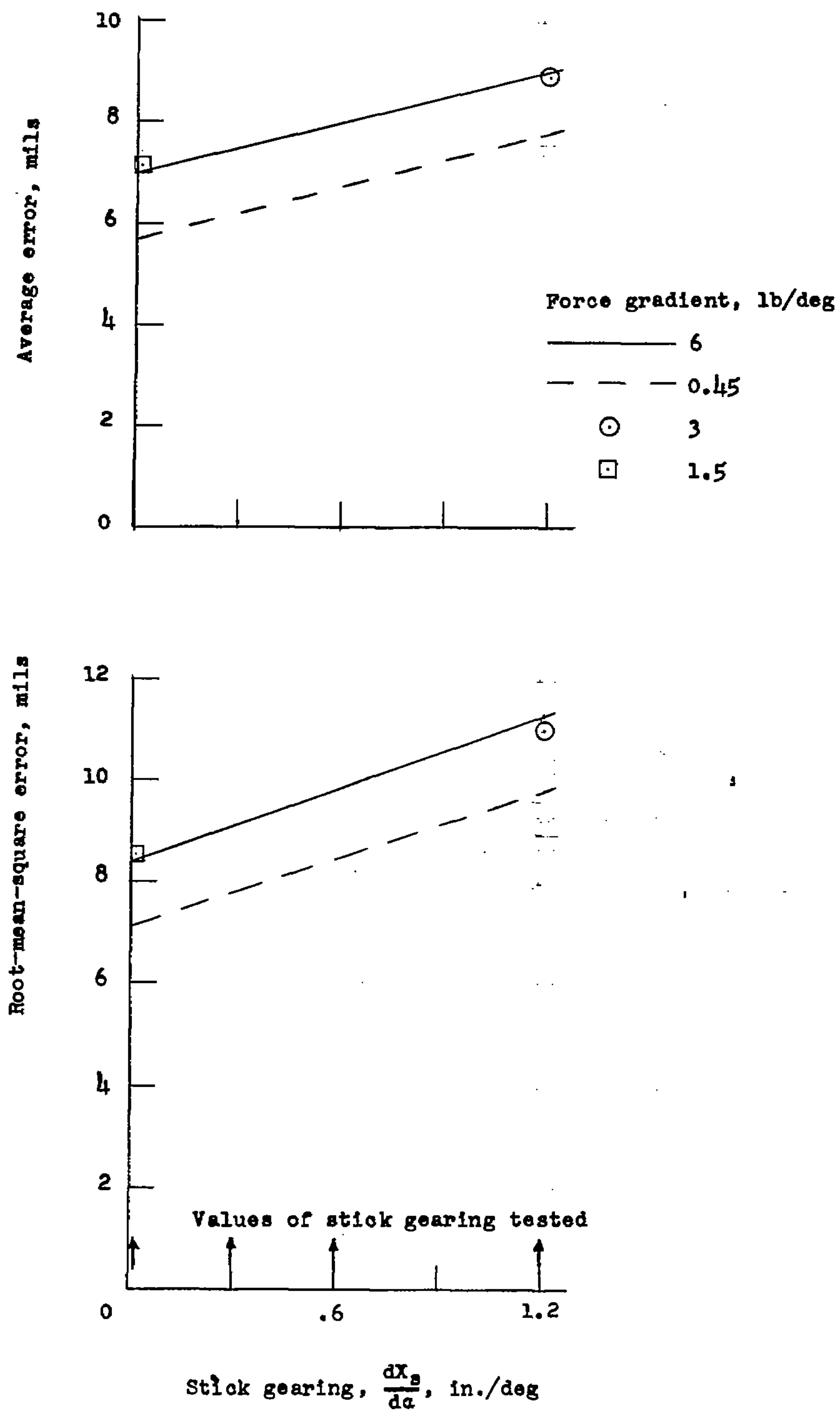


Figure 9.- Variation of representative tracking error with stick gearing for average pilot for values of stick gearings of 0.015, 0.3, 0.6, and 1.2 inches per degree.

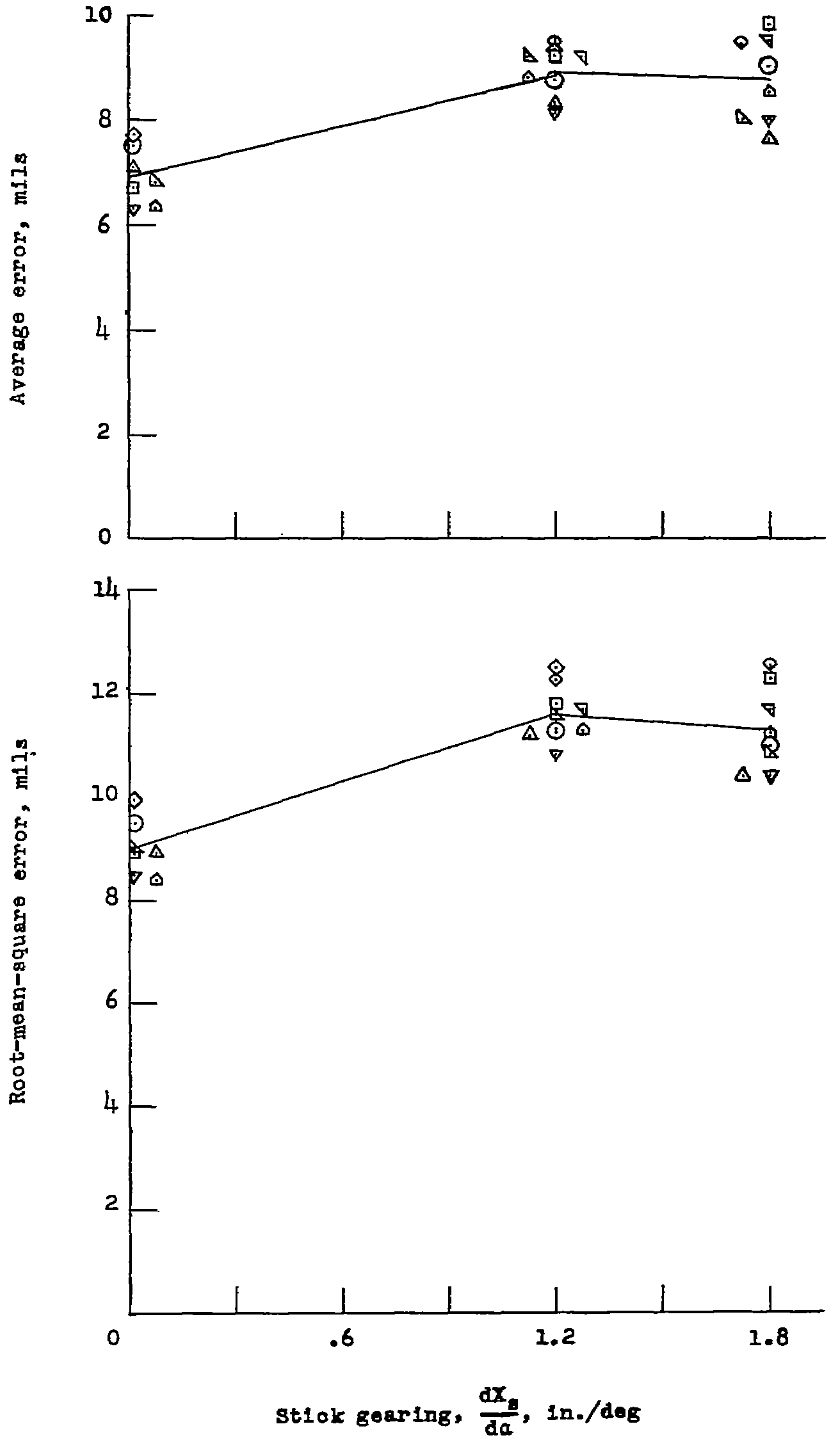


Figure 10.- Variation of representative error for gust type of input with stick gearing for force gradient of 6 pounds per degree. Test-point symbols indicate different subjects.